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Strength and Durability of Low-Cost, High-Performance Concrete

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Research efforts in the last 30 years into understanding the mechanisms of cement hydration and the benefits of using alternative materials to replace cement have been responsible for a great improvement in concrete strength and durability.

These improvements are of significant importance to the Corps of Engineers because of the large volume of cement the Corps uses every year, and because of the high demands we place on performance and durability of the structures we build. In the middle years of this past century, "high performance" of concrete was measured in terms of high strength, and high strength meant using high cement-content mixtures with low water-cement ratios. Compressive strengths of 45 to 50 MPa were considered high strength then, and durable concrete had approximately a 50-year life span. Today, with the many improvements that have been made, high performance can mean many things, and we are routinely capable of producing strengths in the range of 100 MPa and often ask for design lives of 90 years or more.

What is high-performance concrete?

High-performance concrete (HPC) means many things to many different people, and rightly so, because the term describes a wide variety of products. High-performance concrete, as described by Paul Zia in the preface of ACI Special Publication 159 (ACI 1994), is "concrete which meets special performance and uniformity requirements that cannot always be achieved by using only the conventional materials and normal mixing, placing and curing practices."

This definition allows us to consider any concrete mixture that serves a specific purpose very well and that is not achievable with conventional materials and mixing practices as a high-performance concrete. Under this definition very high-strength concrete and very low-strength, highly flowable concrete are both considered high-performance concretes.

For most Corps of Engineers needs, high-performance concrete will mean high strength and excellent durability. We are interested in producing concrete that has superior strength, is cost effective, and will last a long time. In a concrete that is well compacted, higher strength is achievable by lowering the water-cement ratio (Neville 1996). We also know that adding silica fume (SF) to the concrete mixture increases the strength by adding pozzolanic material to the mixture and filling in the small voids that are created between cement particles. Good compaction is important because it reduces voids in the hardened concrete. Voids produce sites where cracking under load can begin and, if connected through a pore structure, can provide a path of ingress of deleterious materials into the concrete structure. It has been said that even 2 percent of voids in concrete will lower the strength by 10 percent (Neville 1996), and permeable concrete promotes damage from freezing and thawing cycles.

Lowering the water-cement ratio also has the effect of lowering the permeability of the concrete. Low permeability is the key to producing durable concrete. High strength is no good if the structure deteriorates after a short life span. Low permeability is achieved either by providing a cement-paste structure with very few, nonconnected voids or by filling the voids in the paste with material that, preferably, is a pozzolan or at least a beneficial filler. If the voids are filled, it will be very difficult for water and other damaging liquids to penetrate into the interior of the concrete and cause durability damage.

All these actions work together to produce high strength and high durability. But these benefits come at a price. Achieving high strength and durability through the use of cement and silica fume is very expensive. Today, the cost of cement is high; but the cost of an equal mass of silica fume is approximately three times that of the cement. It is to our advantage to minimize these expensive materials in the concrete we produce and to substitute less expensive alternatives for these materials and perhaps achieve additional benefits from their substitution. To add low cost to the equation of high-performance concrete, we need to consider using replacement materials such as pozzolans and alternative cementitious materials for cement and silica fume.

Benefits of replacement materials

The three most often used materials to replace portland cement are fly ash; silica fume; and ground, granulated, blast-furnace slag (referred to herein as slag). Two of these (fly ash and silica fume) are pozzolans, while slag is an alternative hydraulic cement. All three of these materials are by-products of other material processes.

There are a number of good reasons to replace a portion of the portland cement in high-performance concrete mixtures with pozzolans and alternative cements. From an economic standpoint, reducing the cost of the raw materials in a cubic yard of concrete by replacing high-cost cement with lower cost pozzolans and alternative cements is an attractive proposition because it reduces the overall cost of the project.

Compared with type I portland cement, class-C fly ash in some areas can cost as little as one third, and slag can be less than half as expensive. Silica fume, on the other hand, is more expensive than cement, although it offers some important features that support its use. In addition to the cost-savings that result, use of alternative cementitious materials saves the energy that would be directed to producing the cement replaced, reduces the production of carbon dioxide, and makes productive use of by-product materials.

As compelling as these reasons are, there are even more attractive features of these replacement materials. They are often better than portland cement in improving some of the important properties of the finished concrete material. Increasing the strength of concrete is one of the primary reasons to use high-performance concrete. Silica fume has been proven to increase the strength because of its highly pozzolanic properties and tiny particle size. The silica fume provides additional amorphous silica to the mixture that can react with the available calcium hydroxide to produce extra calcium-silicate-hydrate (C-S-H) the cementing material in concrete. Also, the very small particle size of silica fume (0.1 to 1 μm) compared with the size of cement particles (10 to 100 μm) allows the silica fume to fit between the cement particles and fill in the space that would otherwise be filled with pore solution. One of the reasons silica fume helps improve the strength of concrete is the additional C-S-H deposited in the pore space.

The other advantage is reduced permeability. Because the silica fume fills the potential void space between cement particles, it reduces the available paths for water and chemical solutions to percolate through the paste and attack aggregate and reinforcing steel. Khayat and Aïtcin (1991) estimated that a 5 percent content of silica fume reduced the coefficient of permeability by an order of three magnitudes. This greatly improves the durability of the concrete by reducing the probability of damage due to freezing and thawing, reducing damage from magnesium, sodium, and calcium chlorides, and enhancing abrasion resistance by providing a stronger, denser paste at the concrete surface.

Even though silica fume has the potential to greatly improve strength and durability, its cost makes it prohibitive for use in large quantities, and research results indicate that large quantities are not good from the standpoint of shrinkage and cracking. Therefore, the goal is to take advantage of the beneficial effects of silica fume while minimizing its impact on increased cost by keeping the amount used to a minimum.

Fly ash and slag are, in their own ways, also beneficial to both strength and durability of concrete. Fly ash is a material composed of round particles that have a chemistry consisting predominantly of glassy silica (in the case of class-F fly ash) and silica and lime (in class-C fly ash). Its particle size is between that of silica fume and cement (1 to 100 μm), so it can often fit in the spaces between cement particles. It also is reactive and produces C-S-H that improves the cement paste microstructure, but at a much slower rate than silica fume. Because the particles are round, there is a reduction in the frictional component in fresh cement paste, which makes the mixture more fluid and easier to place for a given water-cement ratio. Also, because fly ash is composed of small particles, it helps make the paste denser and limits bleeding, so finishing of cement paste with fly ash is often easier. Concretes containing fly ash are generally weaker than ordinary portland cement (OPC) concretes for the first 7 days, but subsequently, they can surpass the strength of OPC. Because fly ash hydrates at a lower rate compared with OPC, concretes made with fly ash produce less heat. This is beneficial from the standpoint of thermal cracking that arises from differential thermal stresses in large concrete structures.

Slag, as it is used in concrete production, is a ground material, so it can be processed to any fineness depending on the amount of energy used to grind it. In terms of fineness, slag normally fits in between silica fume and OPC. Standard practice in the United States generally dictates that less than 80 percent of the mass of slag will have particle size smaller than 45 μm. According to Neville (1996), a mixture of OPC, slag, and high-range, water-reducing admixture can beneficially influence bleeding, setting time, heat-of-hydration development, and mechanical and durability properties. Since slag is a hydraulic cement, it can hydrate in the presence of water to produce C-S-H, in addition to that produced by the hydration of OPC. Its small particle size improves the density of the microstructure, reduces the permeability of the paste, and increases the strength of the mixture in ways similar to silica fume and fly ash. Since fly ash and slag are cheaper than portland cement, it will be beneficial in terms of cost to use these in most concrete mixtures.

Experimental program

Description

As a part of a larger project under the High-Performance Materials and Systems (HPM&S) Research Program, an experimental program was conducted to study the strength and durability response of cement-replacement mixtures containing slag, silica fume, and fly ash. It was the purpose of this set of experiments to find what combinations of these replacement materials provided high strength and good durability. A compressive strength target was set at 100 MPa at 28-days age. Durability was measured as a durability index determined by using ASTM C 666 (2000) as a rapid freezing and thawing testing regime.

Materials studied

This study was based on combining representative volumes of all three replacement materials with type I cement to produce quaternary mixtures of cement, silica fume, fly ash and slag. The volume percentages of replacement materials that were studied in this portion of the project are listed in Table 1.

Table 1. Replacement Material Percentages Studied

Material	Vol. % Studied
Grade 100 slag	10, 15, 20
Silica fume	6, 8, 10
Type C fly ash	15, 20, 25, 30

NOTE: Cement comprised the remainder.

Because silica fume is expensive, its volume was limited to a maximum of 10 percent. Type C fly ash was chosen at the levels shown in the table because of its high lime content and potential to produce extra C-S-H. Grade 100 slag was selected for these studies because it represented a middle grade of slag. The amount of cement that was used in the mixture was allowed to vary as needed to complete the volume percentage of the material (100 percent). An experimental design procedure was used to choose the mixtures that would be made in the study (Table 2).

Table 2. Experimental Mixture Design

Mixture	%Slag	%SF	%FA	%Cem.
1	10	6	15	69
2	10	6	25	59
3	10	8	30	52
4	10	10	15	65
5	10	10	30	50
6	15	6	30	49
7	15	8	20	57
8	20	6	15	59
9	20	6	25	49
10	20	8	30	42
11	20	10	15	55
12	20	10	30	40

All mixtures were made using a laboratory rotary-drum mixer. Cylinders (4- by 8-in. (102- by 203-mm)) were cast from the mixtures for 7-, 28-, 56-, and 90-day compressive strength. Three beams for each mixture (3.5 by 4.5 by 16 in. (89 by 114 by 406 mm)) were cast for freezing and thawing experiments using the ASTM C 666 rapid freezing and thawing durability test. After casting, all specimens were stripped from their molds at 24-hr age and stored in a 100-percent relative humidity environment until testing. Compressive strength tests were conducted on a 440,000-lbf (1.96 million-N) Baldwin universal testing machine.

The rapid freezing and thawing experiments give a number, called the *durability factor*, that is a measure of the resistance of the mixture to freezing and thawing damage. It is a number between 0 and 1 that is based on the relative dynamic modulus of elasticity (P_c) of the beam calculated from fundamental frequency measurements taken at the start of the test (n_0) and after a recorded number of freezing and thawing cycles (n_1). The durability factor (DF) is calculated from the relative dynamic modulus of elasticity (P_c), the number of cycles at which the dynamic modulus reaches a specified minimum, the number of cycles at the termination of the test (N), and the specified number of cycles after which the test will be terminated (M). The equations describing the relationship are given by

$$P_c = (n_1^2 / n_0^2)$$

and

$$DF = P_c \frac{N}{M}$$

Results and discussion

Strength experiments

The results of the compressive strength tests for 7 through 90 days are given in Table 3 and shown graphically in Figure 1. The strength results are the average of three cylinder breaks. All mixtures achieved at least 88 MPa by 28-days age and by 90 days, 10 of the 12 mixtures had exceeded 100 MPa (Table 3; Figure 1). Most mixtures had achieved almost all of their ultimate strength gain by 28- or 56- days age. During the first 28-days age the cement and silica fume provided most of the strength. The slag and fly ash, being materials that hydrate more slowly, provide very little strength at early age and were responsible for most of the additional strength gain beyond 28-days age.

Table 3. Compressive Strength Results (MPa) for 7-, 28-, 56-, and 90-Day Tests

Mixture	7-day	28-day	56-day	90-day
1	75.85	96.22	97.27	103.78
2	77.17	99.83	106.93	111.80
3	70.28	93.60	100.81	101.65
4	72.36	88.36	88.63	92.14
5	76.40	108.46	115.14	112.05
6	77.79	99.51	98.97	105.01
7	79.02	98.07	99.53	94.03
8	76.43	93.72	94.87	100.19
9	74.32	93.53	104.22	108.36
10	74.53	91.99	101.99	103.74
11	86.72	104.23	113.56	113.61
12	78.38	93.22	109.47	109.99

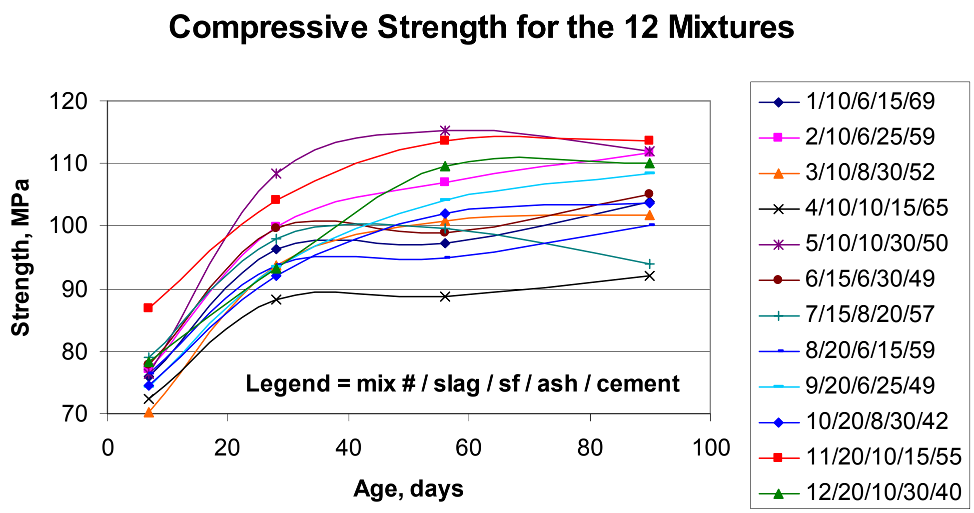

Figure 1. Plot of compressive strength versus age for the 12 mixtures

Several mixtures showed a decrease in strength as time progressed. Mixture 5, which recorded the greatest strength gain, shows a drop of 3 MPa between 56 and 90 days. Mixture 7 decreases from 99.5 to 94 MPa between 56 and 90 days. Mixture 6 also shows some uncertain results at later age, with 56-day strength lower than the 28-day strength. These data are most likely the results of low cylinder breaks at the later ages, as it is unlikely that the strength would decrease.

From the 12 mixtures, the strongest are mixtures 5, 11, and 2, all with approximately 100 MPa at 28 days and 107 to 112 MPa at 90 days. At 7-days age, two of these mixtures (5 and 2), are among the weaker mixtures and the remainder (mixture 11) has the highest strength, 87 MPa. All three mixtures contain 50 percent or more of cement. Mixture 11 contains high slag, high silica fume, and low fly ash; mixture 5 contains low slag, high silica fume, and high fly ash; and mixture 2 contains low slag, moderate silica fume, and high fly ash. The other mixture that had high strength at 7 days, mixture 7, contained moderate slag and fly ash, and low silica fume.

It is difficult to assess the true effects of the additions from just the strength versus age results. As shown in Table 1, there are three supplemental cementitious materials involved each of which is represented at three or four levels of volume replacement of the cement. These variables represent all the main level independent variables to be considered. In addition, there could also be interactions and nonlinear effects of these variables that are important and which may not be apparent in a plot of strength versus age. To gain a different perspective on the effects of the variables, several nonlinear regression analyses were performed on the data to produce models of the data that could help discover which variables were important and if interactions and nonlinear effects were prominent.

The description of the nonlinear regression analysis is beyond the scope of this article. There are many good texts that go into great depth in describing the details of this technique of analyzing complex data. To simplify the process we will present the variables studied, the variables that proved to be the most influential and present some graphs of model data coupled with actual test data. The full complement of variables that were used in our studies includes the main variables, the interactions among the main variables, and the squared effects (Table 4). Although the list is fairly comprehensive, there may be important variables missing from the list, and there is no guarantee that just because they were studied is an indication that they have an effect on the physical properties. These independent variables along with the dependent variable of the 28-day strength were input into the nonlinear correlation analysis software and analyzed to develop a model that used the independent variables that were the most significant in describing the dependent variable of strength.

Table 4 – Variables Studied for Model

Main Var.	Interactions	Squares
Cement	Cem x Ash	Cement^2
Ash	Cem x SF	Ash^2
Silica Fume	Cem x Slag	Silica Fume^2
Slag	Cem x Water	Slag^2
Water	Ash x SF	Water^2
Sand	Ash x Slag	Sand^2
Coarse Agg.	Ash x Water	Coarse Agg^2
	SF x Slag	
	SF x Water	
	Slag x Water	
	Cem + Ash	
	SF + Slag	
	Total cementitious material	
	Water / Cement	

The analysis that resulted in the best fit of the data that also made good sense from a strength standpoint included the independent variables of ash, silica fume and slag, and the interactions of cement × slag, and ash × water. All the remaining independent variables had negligible effect on the correlation of the model and the observed data. The software calculates a coefficient of multiple determination to describe how much of the variation in the dependent variable is described by the model. A value of 0 says that none of the variation is described by the model and a value of 1 says that 100 percent of the variation has been described by the model. In this instance the coefficient was 0.991. The equation that described the variation is

$$y = -90.43 + 3.587(ash) + 1.135(SF) - 0.0046\,(slag^2) + 0.0036(cem)(slag) – 0.0018(ash)(water)$$

where *y* is the 28-day compressive strength (in megapascals) and *cem*, *SF*, *slag*, *ash*, and *water* (in kilograms) are the materials needed to make 1 m^3 of concrete. The mass of water in the mixture was chosen to produce a water-cementitious material ratio in the range from 0.24 to 0.27. The two most important variables in the model were the ash and the slag, occurring in four of the five model terms. The interaction of cement with slag was important since it also added to the increase of strength and showed the effect of the combination of the slag with the cement at 28-days age.

It is interesting to note that cement did not come into the model as a main variable, but as an interaction with the slag. At 28-days age the cement has already made most of its contribution to the material strength. Slag generally produces strength at later ages so its influence probably would commence subsequent to 28 days and the model implies that there is a positive interaction between the two. Silica fume also appears in the equation in a role of a main variable. In all models considered, the silica fume generally acted to increase the strength of the mixture, but different levels of silica fume didn't change the shape of the models. As one might expect, the main variables of sand and coarse aggregate weren't important. Their masses in the mixtures did not vary significantly so their affect on the strength was not significant.

The model given above can be graphed to show some of the effects on strength of varying the levels of materials in the mixture. Figure 2 is a surface plot of the 28-day compressive strengths predicted by the above model. Strength is plotted on the z-axis, mass of slag on the x-axis and mass of C-fly ash on the y-axis. The variables of mass of silica fume and mass of water are fixed at 38 and 170 kg/m^3, respectively. The surface plot implies that increasing both the amount of slag in the mixture and the amount of ash will have the effect of increasing its 28-day strength. The red ellipse on this surface plot identifies areas of the model where predictions are matched by actual strength data collected in the laboratory. The model is capable of predicting strengths outside this range, but there is no guarantee that when the model is predicting outside the limits of collected data that it is accurate. For instance, a mixture containing 127 kg of slag, 168 kg of fly ash, 38 kg of silica fume and an unspecified mass of cement since it is not part of the model predicts compressive strengths in excess of 140 MPa. This is outside the limits of collected data and an unrealistic estimate of 28-day strength for these types of mixtures. Within the red ellipse predictions are more accurate, however trends shown by the surface plot are still valid and present a useful tool in understanding the way in which complex mixtures behave.

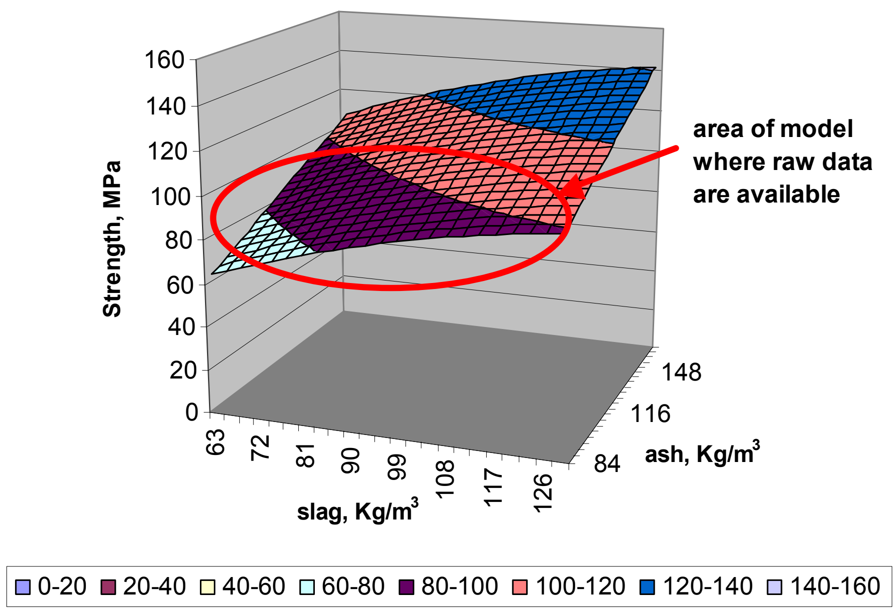

Figure 2. Surface plot of 28-day compressive strength model

The interaction between the slag and cement in the model is significant. A surface plot of the model presented above in terms of cement vs. slag is shown in Figure 3. This plot reveals the interaction between the two materials. At low mass of cement (285 kg/m^3), the increase in the mass of slag from 63 to 127 kg/m^3 changes the compressive strength by a very small amount (Figure 3). However, at high levels of cement in the mixture, increasing the mass of slag has a more significant effect on increasing the compressive strength. This can be seen more clearly in the two-dimensional plot of strength versus mass of slag for the three levels of 285, 390, and 525 kg/m^3 of cement shown in Figure 4.

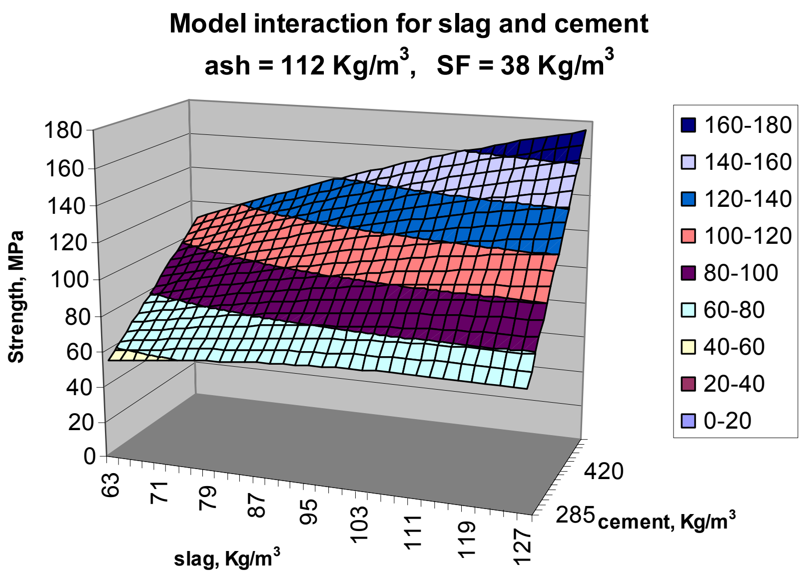

Figure 3. Surface plot of 28-day strength, interaction of slag and cement

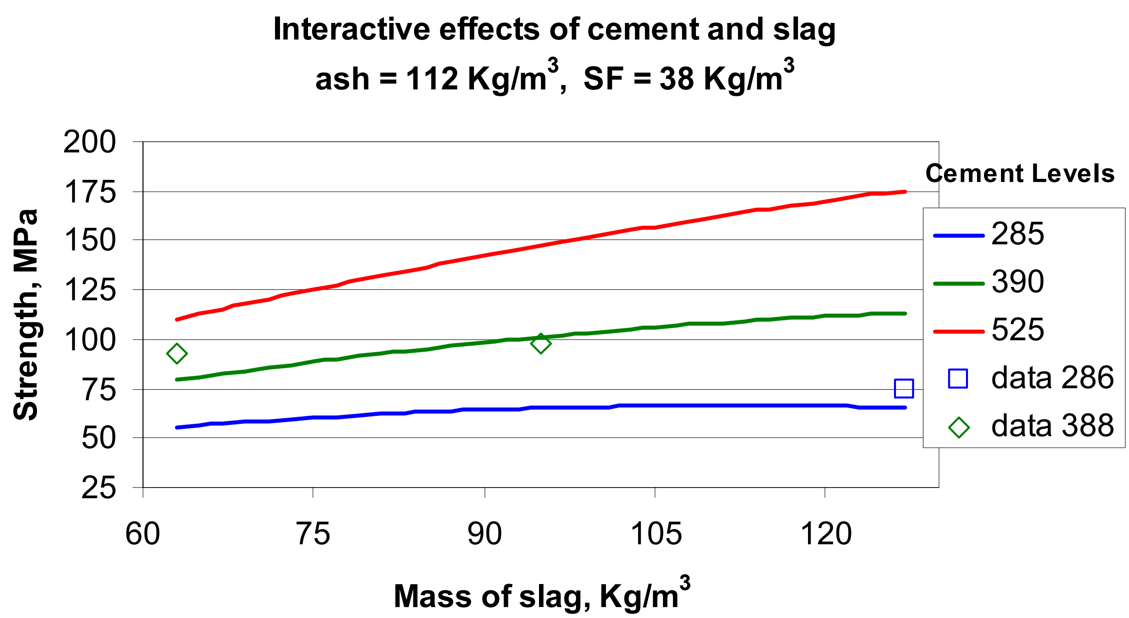

Figure 4. Interaction effect of cement and slag on 28-day strength

In the 12 mixtures studied in this phase of the work, the total mass of cementitious materials ranged between 619 and 725 kg/m^3. At low levels of cement in the mixture there must be more of the other cementitious materials (silica fume, ash, and slag) in the mixture. Fly ash and slag provide their contributions to overall strength at later ages leaving the cement and silica fume to be the active ingredients at 28-days age. The different amounts of cement account for the differences in level of strength, but the changing slope of the lines in the graph indicates that there is an interaction between the cement and slag and that the presence of the slag is beneficial even as early as 28 days. Once again, the actual strength data are represented in the lower regions of the model.

Durability experiments

The beams from the twelve mixtures were subjected to the ASTM C 666 rapid freezing and thawing test to determine the durability factor. The three beams from each mixture were averaged to produce the aggregate durability factor for each mixture shown in Table 5. The mixtures have been displayed in descending order of durability along with the percentages of cement and replacement materials for each mixture. Mixtures 1 and 2 were not tested in the durability experiments so the results were analyzed based on the remaining 10 experiments.

Table 5 - Ranked Durability Results and Associated Mixture Data

Mixture	Durability	%Slag	%SF	%FA	%Cem
10	0.85	20	8	30	42
8	0.64	20	6	15	59
11	0.58	20	10	15	55
12	0.54	20	10	30	40
9	0.52	20	6	25	49
7	0.40	15	8	20	57
3	0.36	10	8	30	52
6	0.34	15	6	30	49
5	0.30	10	10	30	50
4	0.21	10	10	15	65

In analyzing the raw data, it can be seen that the mixtures with the five highest durability factors are the mixtures with 20 percent slag replacement. The mixtures with 15 percent slag replacement are in the middle of the ranking, and the lowest two have 10 percent slag. It can also be seen that the mixture with the highest amount of cement had the lowest durability factor and one of the lowest in cement had the highest durability factor. These observations imply that more slag in the mixture is good for durability and that low cement content does not hamper that result. Inferences about the influence of silica fume and fly ash are hard to make from this view of the data.

In a manner similar to the analysis of the strength experiments, the results of the durability experiments were studied using nonlinear regression analysis. The same set of variables were used to fit a model to the data and a regression equation was chosen that had a coefficient of multiple determination of 0.90 and was of the form:

$$Y = -1.45 - 0.13(\text{slag}) + 0.65(\text{silica fume}) + 0.005(\text{slag}^2) - 0.04(\text{silica fume}^2)$$

where Y is the durability factor and slag and silica fume are given in percentages of cementitious materials. It can be seen from this model that the amount of slag and silica fume were important, and that the amount of fly ash and cement were not. Because of their lack of importance they did not enter the model.

The response surface described by this model is shown in Figure 5, and a two-dimensional representation of slices of the model surface at 8- and 10-percent silica fume is given in Figure 6 with raw data points superimposed for reference. It can be seen from these figures that the model shows that the durability of the concrete greatly improves as the percentage of slag in the mixture is increased. As seen in Figure 5, the durability increases nonlinearly as the percent slag replacement is increased from 10 to 20 percent. Silica fume also has an effect on the durability of the mixtures.

Looking at both Figures 5 and 6, it can be seen that the influence of silica fume is the greatest at about 8 percent and at the lower and higher ends of its tested range it produces mixtures that have a lower durability factor. This can perhaps be seen better in Figure 6 where actual data points have been placed with the model for reference. The model at 8 percent silica fume level produces higher durability factors than the model at the 10 percent level or the 6 percent level (not shown in the figure). As well, there is a nonlinear effect as can be seen in the figure and in the squared terms from the model equation.

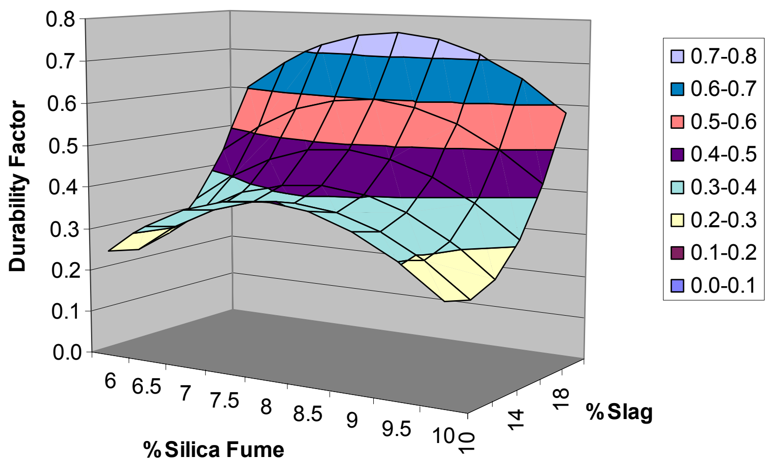

Figure 5. Response surface generated from the durability regression analysis equation

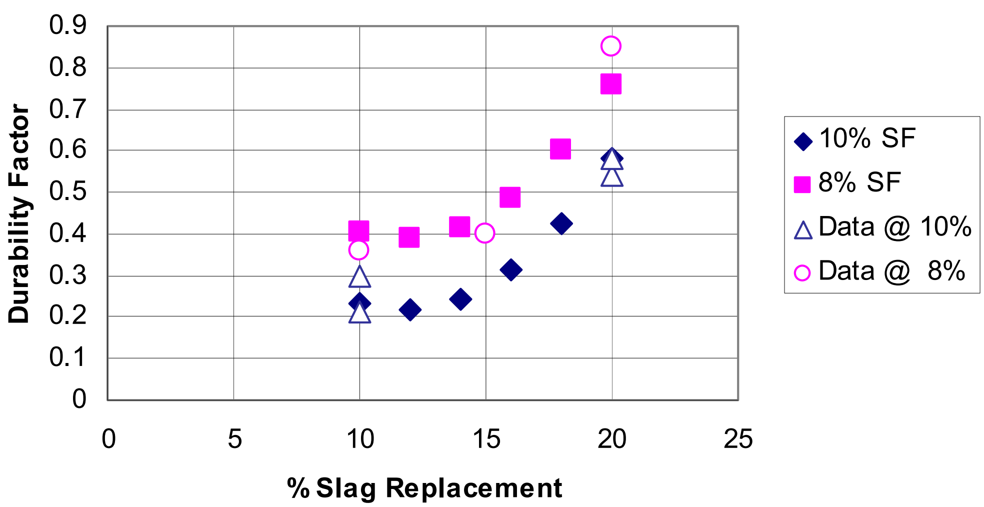

Figure 6. Variation of the durability factor with percent slag replacement

Several important points can be discussed here. First, although the importance of silica fume to strength and durability has been adequately demonstrated in the literature, the data in this study suggest that when combined with slag and fly ash as replacements for portland cement the upper end of the documented silica fume replacement volume (approximately 12 to 15 percent) does not produce the best durability results. This is fortuitous because silica fume is the most expensive material in the mixture. To reduce cost, it is to our advantage to use only what is necessary. Second, it should be remembered that even though there is a positive, nonlinear relationship among the amount of slag, the amount of silica fume, and the durability factor, the increase of durability cannot continue indefinitely. As the volume of replacement materials increases, the volume of cement must decrease and eventually there will be insufficient cement left in the mixture to provide for the needed strength and durability.

In this study, the mass of cement and silica fume in the mixture was kept at a level high enough to produce a compressive strength of approximately 100 MPa by 90 days age. That amounted to between 57 and 77 percent of the cementitious materials being devoted to cement and silica fume, leaving only 23 to 43 percent to be occupied by slag and fly ash. In developing this phase of the work we chose to study between 10 and 20 percent slag. This range was not sufficiently broad to explore the upper end of the potential durability improvements offered by slag replacement.

Conclusions

This article is about the benefits of using pozzolans and alternative cementitious materials to replace portions of the portland cement in concrete mixtures that will have high strength and good durability. What is reported here is only a portion of a much larger study on the strength, durability, and cost of low-cost, high-performance concrete mixtures that use fly ash, slag, and silica fume to replace portions of the cement. The results of the larger study should be available in FY 02 as a document under the HPM&S Program.

In the portion of the study presented here twelve mixtures were proportioned that would achieve high strength in addition to meeting the durability requirements of ASTM C 666. Although the results presented here are abbreviated, it can be concluded that concrete mixtures replacing between 31 and 60 percent of portland cement with pozzolans and alternative cements can achieve compressive strengths of 100 MPa at age 90 days. The strengths achieved are the result of using a very low water-cement ratio to ensure that no excess water remains present in the paste to create capillary pores, a high-range, water-reducing admixture to provide for workability and complete compaction, and by using a combination of cementitious materials that have a range of particle diameters that help assure that the spaces between the larger cement particles are filled with materials that will produce extra calcium-silicate-hydrate. This combination provides for high strength as a result of a densely packed mixture with very few voids and good durability as a function of very low permeability.

The results of the 28-day compressive strength tests were analyzed by conventional means and by using nonlinear regression analysis to identify variables that contributed to the strength in a significant manner. It was observed that the mixtures that achieved the highest strengths at 28 days all contained greater than 50 percent cement. Additionally, the two variables that surfaced from the regression analysis as being the most significant were cement and fly ash. From this analysis the amount of cement was important in defining the level of strength at 28 days, and the interaction between the cement and fly ash implied that there was a beneficial relationship between the two materials that increased the strength more than the individual components.

From these results it can be concluded that at 28-days age, the strength of the concrete is still mainly dependent on the portland cement in the mixture, but that the strength contributions of the fly ash are beginning to become apparent. It can also be said that to achieve a compressive strength of 90- to 100 MPa by 56 days age, the percentage of the cementitious materials that comprise portland cement should be at least 40 percent.

The results of the durability tests were also analyzed conventionally as well as by regression analysis. It was noted from the results of the rapid freezing and thawing tests that the five mixtures with the highest durability factors contained the high level of slag, and the mixtures with the highest and the lowest durability factor contained the lowest and the highest amount of portland cement respectively. From the regression analysis performed on the durability factor results, it was found that the presence of slag and silica fume were important variables in the mixture. The regression analysis showed that the durability factors increased nonlinearly with increase in the percentage of slag from 10 to 20 percent and that an optimum amount of silica fume in the mixture was at about the 8 percent level. From these results it can be concluded that the use of ground granulated blast furnace slag (slag) as a replacement for portland cement helps to increase the durability of the resulting concrete. It is also concluded that silica fume is important in increasing the durability of the concrete and in these mixtures it was found that the optimum amount of silica fume was not at its highest level of inclusion, but rather at a lower percentage, 8 percent. The optimum percentage of slag was not found in this study because the percentages used were too low.

The material costs of the twelve mixtures in this phase of the program were not studied. Cost analysis is studied in another phase of this work, however, it can be stated that the costs of each of these mixtures is lower than that of a similar mixture using only portland cement due to the lower cost of the alternative cementitious materials used.

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